

Neutral top-pion and top-charm production in high energy e^+e^- collisions

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Abstract

We calculate the contributions of the neutral top-pion, predicted by topcolor-assisted technicolor (TC2) theory, to top-charm production via the processes $\gamma\gamma \longrightarrow \bar{t}c$ and $e^+e^- \longrightarrow \gamma\gamma \longrightarrow \bar{t}c$ at the high energy linear e^+e^- collider (LC) experiments. The cross section is of order $10^{-2}pb$ in most of the parameter space of TC2 theory, which may be detected at the LC experiments. So the process $e^+e^- \longrightarrow \bar{t}c$ can be used to detect the signature of TC2 theory.

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It is often stated that the large value of the top-quark mass opens the possibility that it plays a special role in current particle physics. Indeed, the properties of top quark could reveal information on flavor physics, electroweak symmetry breaking (EWSB) as well as new physics beyond standard model. One of these consequences is that the flavor changing scalar coupling (FCSCs) at the tree level would exist at high mass scales. The measurement of FCSCs involving a top quark would provide an important test for the various beyond standard models [1, 2].

Topcolor-assisted technicolor (TC2) theory [3] is an attractive scheme in which there is an explicit dynamical mechanism for breaking electroweak symmetry and generating the fermion masses including the heavy top quark mass $m_t = 175\text{GeV}$. In TC2 theory, the EWSB is driven mainly by technicolor (TC) interactions, the extended technicolor (ETC) interactions give contributions to all ordinary quark and lepton masses including a very small portion of the top quark mass, namely $m'_t = \varepsilon m_t$ [4] with a model-dependent parameter ε ($0.03 \leq \varepsilon \leq 0.1$). The topcolor interactions also make small contributions to the EWSB and give rise to the main part of the top quark mass $m_t - m'_t = (1 - \varepsilon)m_t$ similar to the constituent masses of the light quarks in QCD. This means that the associated top-pions π_t^0 , π_t^\pm are not the longitudinal bosons W and Z , but separately, physically observable objects. Thus top-pions can be seen as the characteristic feature of TC2 theory. Studying the possible signatures of top-pions at high energy colliders can be used to test TC2 theory.

Based upon the observation that the couplings of the charged top-pions π_t^\pm to charm and bottom quarks can be large due to a significant mixing of the top and charm quarks, H.-J. He and C.-P Yuan [5] have studied the possibility of detecting the charged top-pions π_t^\pm at colliders. In Ref.[6], G.Burdman has considered the prospects of the observation of the neutral top-pion π_t^0 via the process $gg \longrightarrow \bar{t}c$ at hadron colliders. In this letter, we consider the process $\gamma\gamma \longrightarrow \pi_t^0 \longrightarrow \bar{t}c$ and see whether π_t^0 can be detected via this process at high energy linear e^+e^- collider (LC) experiments. Our results show that this process is important in probing the flavor-charging top-charm-scalar couplings. If the parameter values of TC2 theory are favorable, the neutral top-pion π_t^0 may be detectable at the LC

experiments.

The possibility of transforming a high energy e^+e^- collider into a photon-photon ($\gamma\gamma$) collider has deserved a lot of attention. For example, Ref.[7] has showed that the top quark pair production in $\gamma\gamma$ colliders is larger than the direct $e^+e^- \rightarrow t\bar{t}$ production both with and without considering the threshold QCD effect. And Ref.[8] has pointed out that the difference beyond standard models, such as the minimal supersymmetric standard model and various TC models, can be distinguished by the process $\gamma\gamma \rightarrow t\bar{t}$ cross section measurement at the high-energy $\gamma\gamma$ colliders. Ref.[2] has showed that the two-Higgs-doublet model which induces FCSCs is more naturally probed via the process $\gamma\gamma \rightarrow \bar{t}c$ than in flavor changing top-quark decays due to the large underlying mass scales and possibly large momentum transfer. The neutral top-pion, as an isospin triplet, can couple to the photons via the top quark triangle loop in an isospin violating way similar to the coupling of QCD pion π^0 to the gluons, and the large isospin violation $(m_t - m_b)/(m_t + m_b) \approx 1$ makes its contribution to the top quark production cross section very important [9]. Thus, in this letter we consider the process $\gamma\gamma \rightarrow \pi^0 \rightarrow \bar{t}c$ and see whether the π_t^0 exchange can mediate top-charm production at interesting levels at the LC experiments.

For TC2 theory, the TC interactions play the major role in breaking the electroweak gauge symmetry, while the topcolor interactions also make small contributions to the EWSB. Thus, there is the following relation:

$$(\nu_\pi)^2 + (F_t)^2 = (\nu_w)^2 \quad (1)$$

where ν_π represents the contributions of TC interactions to the EWSB, $F_t = 50\text{GeV}$ is the top-pion decay constant, and $\nu_w = \nu/\sqrt{2} = 174\text{GeV}$.

For TC2 theory, it generally predicts three light top-pions with large Yukawa coupling to the third family. This induces distinct new flavor changing scalar coupling. The relevant flavor changing scalar couplings including the $t - c$ transition for the neutral top-pion can be written as [3, 5, 6]:

$$\frac{m_t}{\sqrt{2}F_t} \frac{\sqrt{\nu_w^2 - F_t^2}}{\nu_w} [k_{UR}^{tt} k_{UL}^{tt*} \bar{t}_L t_R \pi_t^0 + k_{UR}^{tc} k_{UL}^{tt*} \bar{t}_L c_R \pi_t^0 + h.c.] \quad (2)$$

where the factor $\sqrt{\nu_w^2 - F_t^2}/\nu_w$ reflects the effect of the mixing between the neutral top-pion π_t^0 and the would be Goldston boson [10]. k_{UL}^{ij} is the matrix element of unitary matrix k_{UL} which the CKM matrix can be derived as $V = k_{UL}^{-1}k_{DL}$ and k_{UR}^{ij} is the matrix element of the right-handed relation matrix K_{UR} . Ref.[5] has shown that their values can be taken as:

$$k_{UL}^{tt} = 1, \quad k_{UR}^{tt} = 1 - \epsilon, \quad k_{UR}^{tc} \leq \sqrt{2\epsilon - \epsilon^2} \quad (3)$$

In the following calculation, we will take $k_{UR}^{tc} = \sqrt{2\epsilon - \epsilon^2}$.

For the top quark triangle loop, the simple Adler-Bell-Jackiw (ABJ) anomaly approach is not sufficient since the top quark mass is only 175GeV . Here, we explicitly calculate the top quark triangle loop and obtain the following $\pi_t^0 - \gamma - \gamma$ coupling:

$$\frac{-N_C e^2 (m_t - m_t') m_t}{12\sqrt{2}\pi^2 F_t} C_0 \pi_t^0 \epsilon_{\mu\nu\lambda\rho} (\partial^\mu A^\nu) (\partial^\lambda A^\rho) \quad (4)$$

where N_C is the color index with $N_C = 3$, $C_0(p_4, -p_4, -p_3, m_t, m_t, m_t)$ is the standard three-point Feynman integral with p_3 and p_4 donating the momenta of the two incoming photons.

Ref.[3, 4] have estimated the mass of the top-pion in the fermion loop approximation and given $180\text{GeV} \leq m_{\pi_t} \leq 250\text{GeV}$ for $m_t = 180\text{GeV}$ and $0.03 \leq \epsilon \leq 0.1$. Since the negative top-pion corrections to the $z \rightarrow b\bar{b}$ branching ratio R_b become smaller when the top-pion is heavier, the *LEP/SLD* data of R_b give rise to certain lower bound on the top-pion mass. It was shown in Ref.[10] that the top-pion mass should not be lighter than the order of 1TeV to make the TC2 theory consistent with the *LEP/SLD* data. However, we restudied this problem in Ref.[11]. Our results show that the top-pion mass is allowed to be in the region of a few hundred GeV depending on the models. Thus the top-pion mass depends on the value of the parameters in the TC2 models. As estimation the contributions of the neutral top-pion π_t^0 to $\bar{t}c$ production, we take the mass of the π_t^0 to vary in the range of $200\text{GeV} - 350\text{GeV}$ in this letter.

Using the above formula, we can obtain the cross section $\hat{\sigma}(\hat{s})$ of the process $\gamma\gamma \rightarrow \pi_t^0 \rightarrow \bar{t}c$ which can be written as:

$$\hat{\sigma}(\hat{s}) = \frac{3e^4 A^2}{32\pi} \frac{\hat{s}(\hat{s} - m_t^2)^2}{\hat{s} + m_t^2} \quad (5)$$

with

$$A = \frac{m_t^3(1-\epsilon)k_{UR}^{tc}}{6\pi^2 F_t^2} \sqrt{\frac{(\nu_w^2 - F_t^2)}{\nu_w^2}} \frac{1}{\hat{s} - m_{\pi_t}^2 + im_{\pi_t}\Gamma_{total}} C_0 \quad (6)$$

where $\sqrt{\hat{s}}$ is the $\gamma\gamma$ center-of-mass energy. Γ_{total} is the total decay width of π_t^0 . The possible decay modes of π_t^0 are $b\bar{b}$, $\bar{t}c$, gg , $\gamma\gamma$, zz and $z\gamma$ for $200GeV \leq m_{\pi_t} \leq 350GeV$. Our calculation results show that the branching ratio $Br(\pi_t^0 \rightarrow \bar{t}c)$ is larger than 85% for $\epsilon \geq 0.01$ and is larger than 98% for $\epsilon \geq 0.03$. In this letter, we assume that the free parameter ϵ is in the region of $0.03 \sim 0.1$, so the total width Γ_{total} can be written as :

$$\begin{aligned} \Gamma_{total} &\simeq \Gamma(\pi_t^0 \rightarrow \bar{t}c) \\ &\simeq \frac{3(1-\epsilon)^2}{16\pi} \frac{\nu_w^2 - F_t^2}{\nu_w^2} \frac{m_t^2 m_{\pi_t}}{F_t^2} (K_{UR}^{tc})^2 \sqrt{1 - \frac{m_t^2}{m_{\pi_t}^2}} \end{aligned} \quad (7)$$

The total cross section $\sigma(s)$ of the process $e^+e^- \rightarrow \gamma\gamma \rightarrow \bar{t}c$ can be obtained by folding the cross section $\hat{\sigma}(\gamma\gamma \rightarrow \bar{t}c)$ with the photon luminosity at the e^+e^- colliders [12, 8]:

$$\sigma(s) = \int_{(m_t+m_c)/\sqrt{s}}^{x_{max}} (dz)(dL_{\gamma\gamma})/(dz)\hat{\sigma}(\hat{s}) \quad (\hat{s} = z^2s) \quad (8)$$

where \sqrt{s} is the e^+e^- centre-of-mass energy and $(dL)_{\gamma\gamma}/(dz)$ is the photon luminosity which is given in Ref.[12].

According to the method used in Refs.[12, 8], we can calculate the subprocess cross section $\hat{\sigma}(\hat{s})$ and cross section $\sigma(s)$. Fig.1 shows the cross sections $\hat{\sigma}(\hat{s})$ for the process $\gamma\gamma \rightarrow \bar{t}c$ as a function of the mass of neutral top-pion π_t^0 at $\sqrt{\hat{s}} = 300GeV$. The cross sections are displayed for the three values of the parameter $\epsilon = 0.05, 0.08$, and 0.1 , respectively. From Fig.1, we can see that the cross sections are not sensitive to the value of parameter ϵ . The peak of each curve emerges at $m_{\pi_t} \sim \sqrt{\hat{s}}$. The maximum value can reach $1pb$ for $m_{\pi_t} = 300GeV$, $\epsilon = 0.05$.

To see the effect of the center-of-mass energy $\sqrt{\hat{s}}$ on the top-charm production rate, we plot the cross section $\hat{\sigma}(\hat{s})$ as functions of $\sqrt{\hat{s}}$ for $\epsilon = 0.08$ in Fig.2, in which the solid, dotted and dashed lines stand for $m_{\pi_t} = 200GeV, 250GeV$ and $300GeV$, respectively. From these curves we find that the cross section can be obviously enhanced when m_{π_t} get close to $\sqrt{\hat{s}}$. $\hat{\sigma}(\hat{s})$ is larger than $10^{-2}pb$ for $m_{\pi_t} \geq 250GeV$.

In Fig.3, we show the cross section $\sigma(s)$ of the process $e^+e^- \longrightarrow \gamma\gamma \longrightarrow \bar{t}c$ as a function of center-of-mass energy of electron-positron system \sqrt{s} with $\varepsilon = 0.08$, $m_{\pi_t} = 200GeV, 250GeV$ and $300GeV$. From Fig.3 we can see that the cross section $\sigma(s)$ of the process $e^+e^- \longrightarrow \gamma\gamma \longrightarrow \bar{t}c$ is very small for $\sqrt{s} < 230GeV$ and the lines go to flat as \sqrt{s} increasing. This is due to : (a) the available range of $\sqrt{\hat{s}}$ is determined by $min(\sqrt{\hat{s}}) = m_t + m_c \simeq 177GeV$ and $max(\sqrt{\hat{s}}) = x_{max}\sqrt{s} = 0.83\sqrt{s}$, so that $max(\sqrt{\hat{s}})$ is s dependent; (b) the $\gamma\gamma$ luminosity $(dL)_{\gamma\gamma}/(dz)$ decreases rapidly in the vicinity of $max(\sqrt{\hat{s}})$ which give rise to a suppression of the large $\sqrt{\hat{s}}$ contributions to $\sigma(s)$; (c) the integrated range of the $\sigma(s)$ is in the range of $(m_t + m_c)/\sqrt{s} \sim x_{max}$ which increase as \sqrt{s} increasing.

To see the effect of neutral top-pion mass on the cross section $\sigma(s)$, we plot $\sigma(s)$ versus as function of m_{π_t} in Fig.4 for $\varepsilon = 0.05, 0.08, 0.1$ and $\sqrt{s} = 500GeV$. From Fig.4 we can see that $\sigma(s)$ is not sensitive to the parameter ε and increases with m_{π_t} increasing. The cross section $\sigma(s)$ varies between $8.5 \times 10^{-3}pb$ and $0.146pb$ as m_{π_t} increases from $200GeV$ to $350GeV$. The reason is that the available $\sqrt{\hat{s}}$ spreads in a wider range of $177GeV \sim 415GeV$ which increase the importance of the contributions of the factor $(\hat{s} - m_{\pi_t}^2 + im_{\pi_t}\Gamma_{total})^{-1}$ and the $\gamma\gamma$ luminosity suppression effect is less significant in this range.

The cross section of the process $e^+e^- \longrightarrow \bar{t}c$ is very small at one loop level in the standard model due to the unitary of CKM matrix. New particles predicted by the beyond standard may have significant contributions to the process $e^+e^- \longrightarrow \bar{t}c$. Therefore this process can be used to test new physics. In this letter, we have discussed and calculated the contribution of the neutral top-pion π_t^0 to the top-charm production via the processes $\gamma\gamma \longrightarrow \bar{t}c$ and $e^+e^- \longrightarrow \gamma\gamma \longrightarrow \bar{t}c$ at the LC experiments. We find that the cross section is of order $10^{-2}pb$ in the reasonable parameter space of TC2 theory. If we assume that the integrated luminosity of high energy photon-photon ($\gamma\gamma$) or electron-positron (e^-e^+) colliders is $50fb^{-1}$, it would produce a few hundred events at the LC experiments. So it is possible to detect the signature of TC2 theory via the processes $e^+e^- \longrightarrow \bar{t}c$ or $\gamma\gamma \longrightarrow \bar{t}c$ at the future LC experiments.

Figure Captions

Fig.1: The cross section $\hat{\sigma}(\hat{s})$ of the process $\gamma\gamma \longrightarrow \pi_t^0 \longrightarrow \bar{t}c$ versus m_{π_t} for $\sqrt{\hat{s}} = 300GeV$ and $\varepsilon = 0.05, 0.08, 0.1$.

Fig.2: The cross section $\hat{\sigma}(\hat{s})$ versus $\sqrt{\hat{s}}$ for $\varepsilon = 0.08$ and $m_{\pi_t} = 200GeV, 250GeV, 300GeV$.

Fig.3: The cross section $\sigma(s)$ of the process $e^+e^- \longrightarrow \gamma\gamma \longrightarrow \bar{t}c$ versus \sqrt{s} for $\varepsilon = 0.08$ and $m_{\pi_t} = 200GeV, 250GeV, 300GeV$.

Fig.4: The cross section $\sigma(s)$ versus m_{π_t} for $\sqrt{s} = 500GeV$ and $\varepsilon = 0.05, 0.08, 0.1$.

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